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# ERRORS IN THE MEASUREMENT OF THE LUNAR TEMPERATURE: Integrated Emissivities of Materials Suspected to Comprise the Lunar Crust

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ABSTRACT

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Application of reflectance spectra of minerals suspected to exist in the lunar crust to the Planck-Wien radiation law permits calculation of emission spectra of these materials. A severe error in temperature measurement of these materials results when the emissivity is assumed to be independent of wave length. The magnitude of this error is dependent upon the method of calculation and composition examined. The results of detailed calculations for a series of minerals which include typical suspected lunar assemblages of granite, obsidian, dunite, chondritic meteorite, and tektite are presented. The calculated temperature dependence of the average emissivity of these materials is given.

AUTHOR

# ERRORS IN THE MEASUREMENT OF THE LUNAR TEMPERATURE

## Integrated Emissivities of Materials Suspected to Comprise the Lunar Crust

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Recently, we have reported (1962, Burns and Lyon) interpretations of the classic 1930 Pettit and Nicholson work of the measurement of the lunar temperature in light of findings generated since 1955 with refined instrumentation. The conclusion of these interpretations is one of skepticism of the reasoning leading to the Pettit-Nicholson thesis that the emissivity of the lunar crust is unity. A detailed criticism of the Pettit-Nicholson work together with calculated values of both the emissivity as a function of wave length and composition, and the average emissivity as a function of temperature and composition are presented below.

The basis of the Pettit and Nicholson conclusions was interpretation of radiometric data obtained with two crude filter monochromators. They found that the ratio (H) of the radiant energy in a wave length interval $8\mu$-to-$10\mu$ to that in a wave length interval of $8\mu$-to-$14\mu$ was 0.37, very close to that calculated for a $400^{0}$K black body viewed through their optics, namely, 0.38. Paradoxically, the temperature of the sub-solar point, ($400^{0}$K), used in the above calculations was obtained using the usual manner by assuming the emissivity to be unity and application of Stefan's law (Pettit, 1961) after relating the measurements to the radio-metric magnitude of a comparison star.

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Pettit and Nicholson state that the only way the two ratios could agree is to have equal emissivities in the regions 8-10μ and 8-14μ. Mathematically,

$$H_{obs} = \frac{\int_8^{10} \epsilon(\lambda)\ W(\lambda,400)d\lambda}{\int_8^{14} \epsilon(\lambda)\ W(\lambda,400)d\lambda} = \frac{\epsilon_{a,400}^{8-10}}{\epsilon_{a,400}^{8-14}} \frac{\int_8^{10} W(\lambda,400)d\lambda}{\int_8^{14} W(\lambda,400)d\lambda} \tag{1}$$

$$= \frac{\epsilon_{a,400}^{8-10}}{\epsilon_{a,400}^{8-14}} H_{bb} \tag{2}$$

$$H_{obs} = H_{bb} \quad \text{when} \quad \epsilon_{a,400}^{8-10} = \epsilon_{a,400}^{8-14} \tag{3}$$

However, using data for the wave length variation of the emissivity of quartz they calculated an H ratio of 0.30 and conclude, surprisingly, the emissivities must be 1.00 over both the 8-10μ and 8-14μ regions. This conclusion is not logically supported by the preceding argument.

In view of recent data (Sloan, 1955; Burch, 1956, 1957; Howard, 1959) concerning the radiative and transmissive characteristics of the earth's atmosphere, we find the Pettit-Nicholson conclusion to be erroneous. These recent data, obtained with vastly improved, refined instruments compared to those available in 1930, show there is sufficient ozone in the atmosphere to absorb 25 per cent of the radiant energy in the 8-10μ region and 16 per cent in the 8-14μ region. Because ozone existed in the atmosphere in 1930, although it had not been defined Pettit and Nicholson should have found

$$H_{obs} = \frac{0.75}{0.84}(0.38) = 0.34, \tag{4}$$

if the average emissivity was unity as they concluded, instead of 0.37. The emission spectrum of a 400°K black body received through ozone in the concentration present in the atmosphere is shown in Fig. A.1. Also shown in this figure is the 400°K emission spectrum of tektite (a much more likely geological assemblage to be found on the surface of the moon than quartz). This figure dramatically shows the ozone causes a lack of sensitivity to radiometric measurements in the vicinity of 8-10μ.

In order to reconcile the unity emissivity conclusion with the varying emissivity in the 8-10μ region observed for silica and silicates (Wood), Pettit and Nicholson further concluded the lunar crust was finely divided, like sand, or porous, like pumice, and its radiating properties would be nearly those of a "black body." This second conclusion was supported by the coefficient of thermal conductivity of the moon calculated from measurements made during the total lunar eclipse of June 14, 1927.

Recent emission measurements by Bell and co-workers (1956, 1957) have indicated that finely divided gypsum sand at White Sands, New Mexico, and quartz sand at Cocoa Beach, Florida, give significant deviations from a blackbody Planck-Wien radiation curve. Two significant facts can be seen from Bell's data shown in Fig. A.2. Firstly, the magnitude of the quartz reststrahlen at 9.08μ is much smaller than that found at higher temperature (McMahon, 1950) or by reflectance techniques (Lyon and Burns, 1962). This is due to two factors: 1) the temperature of measurement is very near to that of the detector temperature; hence emission from the optics, chopper blades, etc., gives a high background and any stray energy will cause a minimization in relative intensities; and 2) the optical resolution afforded by the Bell equipment is such that fine structure (Lyon and Burns, 1962) will be integrated into the over-all emission curve. Secondly, qualitative identification by remote infrared emission spectral measurements is available. In spite of the experimental difficulties in this measurement, quartz and gypsum are clearly distinguishable from each other by the 0.49μ wave length shift of emission minimum.

As a result of the lack of sensitivity of measurement in the 8-10μ regions, together with the failure to observe a ratio corresponding to recently established transmissive characteristic of the earth's atmosphere, the arbitrary choice of the 400$^{o}$K as the temperature of the subsolar point, and the fallacy of sand-size particle behaving as a "black body," we must view with skepticism the Pettit-Nicholson conclusion that the emissivity of the moon is unity.

Because of the earth's ozone concentration in the atmosphere, meaningful spectral emission curves can not be made terrestrially as has been demonstrated by Adel (1946). Therefore, temperature measurements and compositional assignments of the lunar crust can only be made above the earth's atmosphere --- from high-altitude balloon measurements or from attitude-controlled orbiting spacecraft.

To aid in interpretation of results to be obtained from measurements above the earth's atmosphere, we have investigated the effect of composition of several materials suspected to exist in the lunar crust on the emissivity vs. wave length curve, and have calculated the radiance, $\mathfrak{R}(\lambda,T)$ at several temperatures. For these calculations:

$$\mathfrak{R}(\lambda,T) = \epsilon(\lambda)\, W(\lambda,T) \tag{5}$$

The $\epsilon(\lambda)$ curve was obtained indirectly with the aid of Kirchhoff's law (Eq. 6):

$$\rho(\lambda) + \alpha(\lambda) + t(\lambda) + s(\lambda) = 1 \tag{6}$$

With polished $[s(\lambda) = 0]$, opaque $[t(\lambda) = 0]$ surfaces, Eq. (6) is simplified to Eq. (7)

$$\alpha(\lambda) = 1 - \rho(\lambda) = \epsilon(\lambda) \tag{7}$$

which indicates that 1, less the reflectivity, is equal to the absorptivity which, at thermal equilibrium, is equal to the emissivity. This simple method permits calculation of $\epsilon(\lambda)$ without the noisome temperature-dependent absolute-radiometric measurements which are subjec to many experimental difficulties. The validity of application of Kirchhoff's law to silica-bearing glasses has been established by McMahon (1950) and Gardon (1956).

The reflectance spectra of typical volcanic rock and lunar materials (meteorites and tektites) are shown in Figs. A.3 and A.4. In Fig. A.3 a serial shift of 160 cm$^{-1}$ (0.85 micron) is seen for the spectral peaks around 920-1080 $cm^{-1}$ as one passes from acid rocks (obsidian, rhyolite, granite, tektite) through those of intermediate composition (andesite and diabase) to the basic and ultra-basic materials (olivine-bearing dunite and chondritic meteorites. Most importantly, the spectral peaks are dependent on bulk composition and do not move in wave length with increasing grain size. Thus, whether a given chemical composition of rock is in the physical form of glass, felsite, fine-grained volcanic flow, medium-grain or coarse-grained plutonic rock, its spectral reflectance maximum will remain fixed in wave length.

Comparison of $\mathcal{R}(\lambda,T)$ curves of four typical proposed lunar materials - granite, obsidian, dunite and chondritic meteorite at 350°K are shown in Fig. A.5. These curves graphically illustrate the effect of compositional changes on the spectral emittance curve. A variation in the average emissivity of approximately 10 per cent exists between granite and dunite. Calculation of the temperature of the moon using Stefan's law

$$T = \left[ \frac{\mathcal{R}}{\sigma\epsilon_a} \right]^{1/4} \tag{8}$$

introduces considerable error when $\epsilon_a$ is assumed to be unity:

$$\frac{dT}{T} = \frac{d\mathcal{R}}{4\mathcal{R}} - \frac{d\epsilon_a}{4\epsilon_a} \tag{9}$$

For example, when $\epsilon_a = .82$ instead of 1.0, $dT/T = -0.045$, or a reported temperature of 350°K is low by 16°K. The variation in $\epsilon_a$ of 10 per cent between composition can superimpose a 2.5 per cent variation in temperature (approximately - 9°K when T = 350°K) by compositional changes above. It follows that the lunar temperature changes reported by Shorthill and Saari (1961) could instead be caused entirely, or in part, by compositional changes.

Upon examination of a single material, assumption that $\epsilon_a$ is independent of temperature is erroneous; because of the dependence of $\epsilon_a$ on wave length, $\epsilon_a$ is also a function of temperature. The temperature variance of the emittance curves for dunite are shown in Fig. A.6. This figure clearly shows that commensurate changes in $\epsilon_a$ for dunite exist as a function of temperature. Calculations similar to those required to make Fig. A.6 were carried out for four other materials suspected to be in the lunar crust; the resultant $\epsilon_a$ for each temperature was calculated and the temperature dependence of $\epsilon_a$ for these materials are shown in Fig. A.7. In the temperature range, 325-450°K, this temperature dependence is nearly linear,

$$\epsilon_a = \epsilon_a^{350} + \beta(T - 350) = \epsilon^{o}_{a} + \beta T \tag{10}$$

Calculated values for $\epsilon_a^{350}$, $\epsilon^{o}_{a}$, and $\beta$ for five materials suspected to exist in the lunar crust are listed in Table I. Combining Eqs. (8) and (10), taking differentials, and simplifying,

$$\frac{dT}{T} = \left[\frac{\epsilon^{o}_{a} + \beta T}{\epsilon^{o}_{a} \quad 5/4\beta T}\right] \frac{d\Re}{4\Re} \tag{11}$$

Therefore, the ratio of the temperature change found, assuming temperature dependence of $\epsilon_a$ to that assuming temperature independence, is

$$(dT)/(dT)_{\epsilon_a} = \frac{(\epsilon^{o}_{a} + \beta T)}{(\epsilon^{o}_{a} + 5/4\beta T)} \tag{12}$$

or for dunite at 350°K, $(dT)/(dT)_{\epsilon_a} = 0.951$. From this discussion it is seen that the dependence of $\epsilon_a$ on temperature is a second-order effect (4.9% low); hence temperature changes of the same material by radiometric methods is valid.

Recent studies (Burns and Lyon, 1963) indicate values of $\epsilon(\lambda)$ obtained from Eq. 7 are not valid when the material under question is in powdered form and corresponding integrated total reflection or emission measurements are made. In general, the same shape of curve is obtained, but the amplitude of the deviations from black body behavior is reduced. This observation is valid for particle sizes as low as 100μ, and in some instances as low as 10μ. Because the $\epsilon(\lambda)$ curves are dependent on particle size, the work presented here gives only the maximum deviations from black body behavior that one could expect to observe. Because the exact surface aggregation state of the lunar surface is not known although it is suspected to be powdered with good reason (Hapke, 1963), caution must be applied when using the data of Table I. Similarly, caution must be exercised when using $\epsilon_a = 1.00$ in temperature determinations from total radiometry and in particular with radiometry through an 8-14μ filter.

Table I. Temperature Characteristics of the Average Emissivity in the Range 325-450°K

| Material | $\epsilon_a^{350}$ | $\epsilon_a^{o}$ | $\beta \times 10^4$ |
|---|---|---|---|
| Dunite | 0.785 | 0.624 | 4.60 |
| Meteorite Chondrite | 0.821 | 0.707 | 3.26 |
| Obsidian | 0.836 | 0.744 | 2.50 |
| Granite | 0.864 | 0.804 | 1.71 |
| Tektite | 0.861 | * | * |

*Linear relationship of Eq. (10) not applicable.

## GLOSSARY OF TERMS

| | | |
|---|---|---|
| $\alpha(\lambda)$ | = | absorptivity as a function of wave length |
| $(dT)_{\epsilon_a}$ | = | change in temperature at constant average emissivity |
| $\epsilon(\lambda)$ | = | emissivity as a function of wave length |
| $\epsilon_a$ | = | average emissivity, defined as $\dfrac{\int_2^{25} \epsilon(\lambda)\, W(\lambda,T)d\lambda}{\int_2^{25} W(\lambda,T)d\lambda}$ |
| $\epsilon_a^{\lambda_1-\lambda_2}$ | = | average emissivity for the wave length range $\lambda_1$ to $\lambda_2$ |
| $\epsilon_a^{T}$ | = | average emissivity at temperature T |
| $\epsilon^{o}_{a}$ | = | average emissivity extrapolated to $0^{o}$K from 325-450$^{o}$K data |
| $\lambda$ | = | wave length |
| $\lambda_m$ | = | wave length of maximum energy in emission curve |
| $\rho(\lambda)$ | = | reflectivity as a function of wave length |
| $\mathfrak{R}$ | = | radiant energy |
| $\sigma$ | = | Stefan's constant |
| $s(\lambda)$ | = | fraction of scattered light as a function of wave length |
| $t(\lambda)$ | = | transmittance as a function of wave length |
| T | = | absolute temperature |
| $W(\lambda,T)$ | = | energy of a black body as a function of wave length and temperature as defined by the Planck-Wien radiation law |

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## FIGURES

## REFERENCES


Adel, A., 1946, The infrared spectrum of the Moon, Ap. J., 103, 19.

Bell, E. E., and Eisner, I. L., 1956, Infrared radiation from the white sands at White Sands National Monument, New Mexico, J. Opt. Soc. Amer., 46, 303.

Bell, E. E., Eisner, I. L., Young, J. B., Abolins, A., and Oetjen, R. A., 1957, Infrared techniques and measurements, Ohio State Research Foundation, Final Engineering Report, Contract AF 33(616) 3312.

Burch, D. E., 1956, Infrared evidence for the presence of ozone in the lower atmosphere, J. Opt. Soc. Am., 46, 360.

Burch, D. E., and Shaw, J. H., 1957, Infrared emission spectra of the atmosphere between 14.5μ and 22.5μ, J. Opt. Soc. Am., 47, 227.

Burns, E. A., and Lyon, R. J. P., 1962, Errors in the measurement of the temperature of the Moon, Nature, 196, 463.

Burns, E. A., and Lyon, R. J. P., 1963, Feasibility of remote compositional mapping of the lunar surface, in "Proceedings of the Lunar Surface Symposium", J. Salisbury and P. Glaser, Editors, Academic Press, in preparation.

Gardon, R., 1956, The emissivity of transparent materials, J. Am. Cer. Soc., 39, 378.

Hapke, B., Photometric and other laboratory studies relating to the lunar surface, in "Proceedings of the 1963 Lunar Surface Symposium", J. Salisbury and P. Glaser, Ed., Academic Press, in preparation.

Howard, J. N., 1959, The transmission of the atmosphere in the infrared, Proc. of I. R. E., 1451.

Lyon, R. J. P., and Burns, E. A., 1953, Analysis of rocks and minerals by reflected infrared radiation, Econ. Geol., 58, 274.

McMahon, H. O., 1950, Thermal radiation characteristics of some glasses, J. Am. Cer. Soc., 34, 91.

McMahon, H. O., 1950, Thermal radiation from partially transparent reflecting bodies, J. Opt. Soc. Am., 40, 376.

Pettit, E., and Nicholson, S. B., 1930, Lunar radiation and temperature, Ap. J., 71, 102.

Pettit, E., 1940, Ap. J., 91, 408.

Pettit, E., 1961, "The Solar System," Vol. 3, "Planets and Satellites," ed. G. P. Kuiper and B. M. Middlehurst, Chicago, University of Chicago Press, Chapter 10.

Saari, J. M., and Shorthill, R. W., 1962, Infrared mapping of lunar craters during the full Moon and total eclipse of September 5, 1960, Boeing Aircraft Co., Rept. D1-82-0176, July.

Shorthill, R. W., and Saari, J. M., 1961, "Lunar infrared temperature during Sept. 4, 5 and 6, 1960," Boeing Aircraft Co., Contract AF 18(600)1824, Jan. 30.

Shorthill, R. W., 1962, Measurements of lunar temperature variations during an eclipse and throughout a lunation, Boeing Aircraft Co., Rept. No. D1-82-0196, August.

Simon, J., and McMahon, H. O., 1953, Study of the structure of quartz, cristobalite, and vitreous silica by reflection in infrared, J. Chem. Phys., 21, 23.

Sloan, R., Shaw, J. H., and Williams, D., 1955, Infrared emission spectrum of the atmosphere, J. Opt. Soc. Am., 45, 455.

Wood, R. W., 1934, "Physical Optics," 3rd Ed. Macmillan and Co., New York.

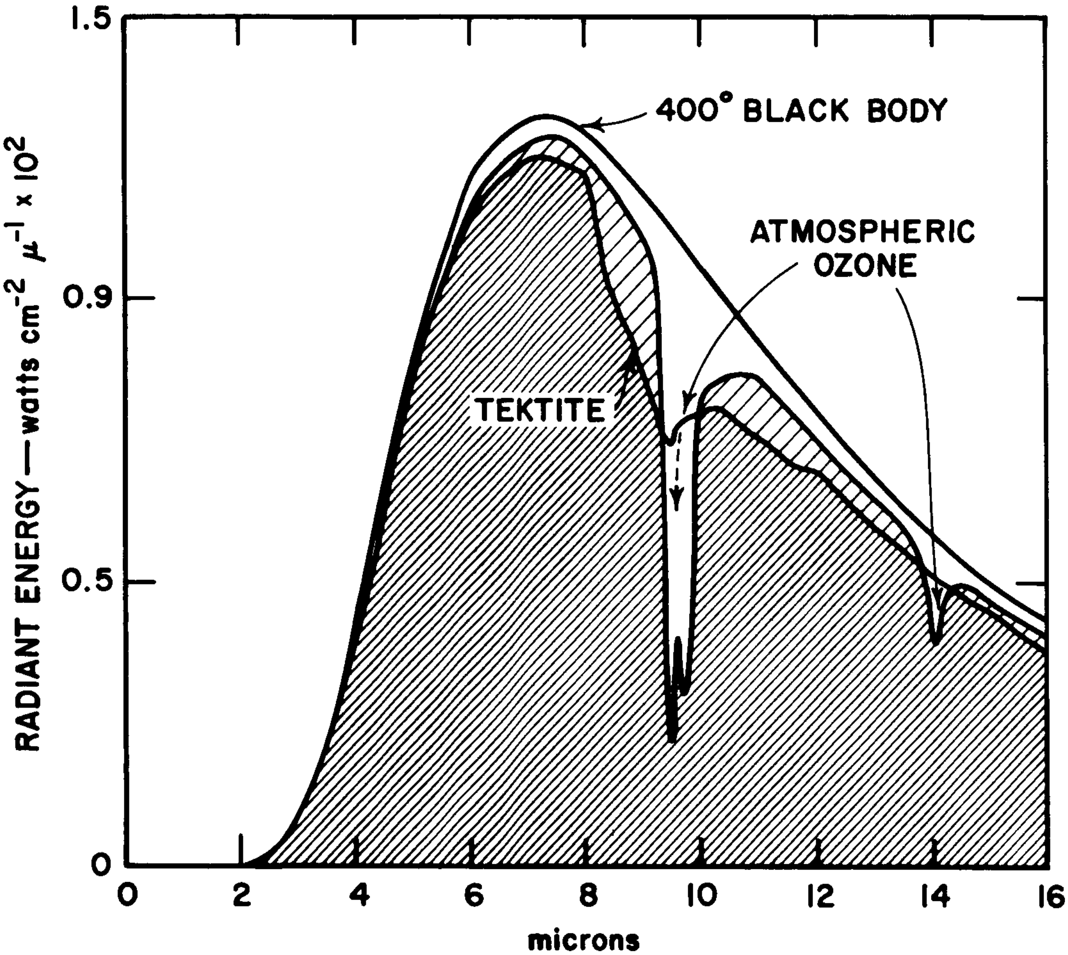


FIG. 1 EMISSION CURVES OF (a) 400°K BLACK BODY, (b) 400°K BLACK BODY SEEN THROUGH ATMOSPHERIC OZONE, (c) 400°K TEKTITE

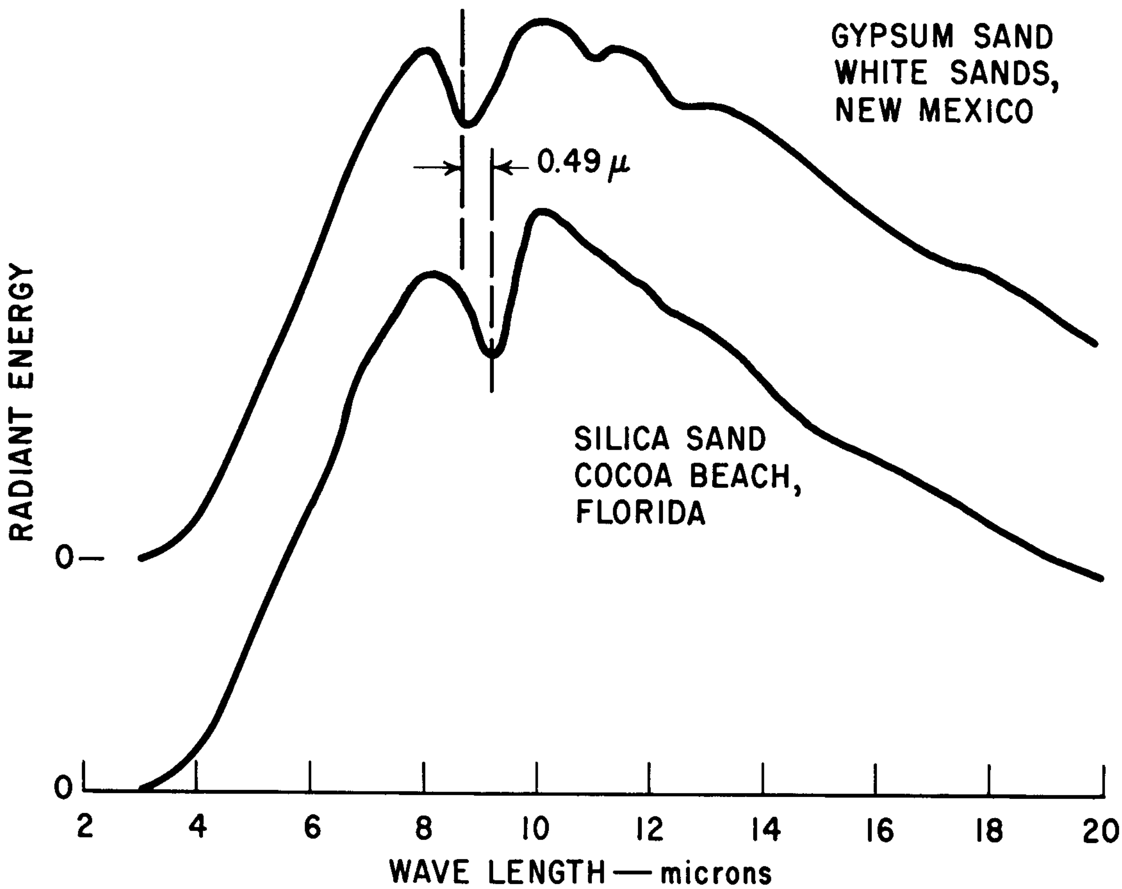


FIG. 2 TYPICAL EMISSION CURVES FOR GYPSUM AND SILICA SAND OBSERVED BY BELL, et al

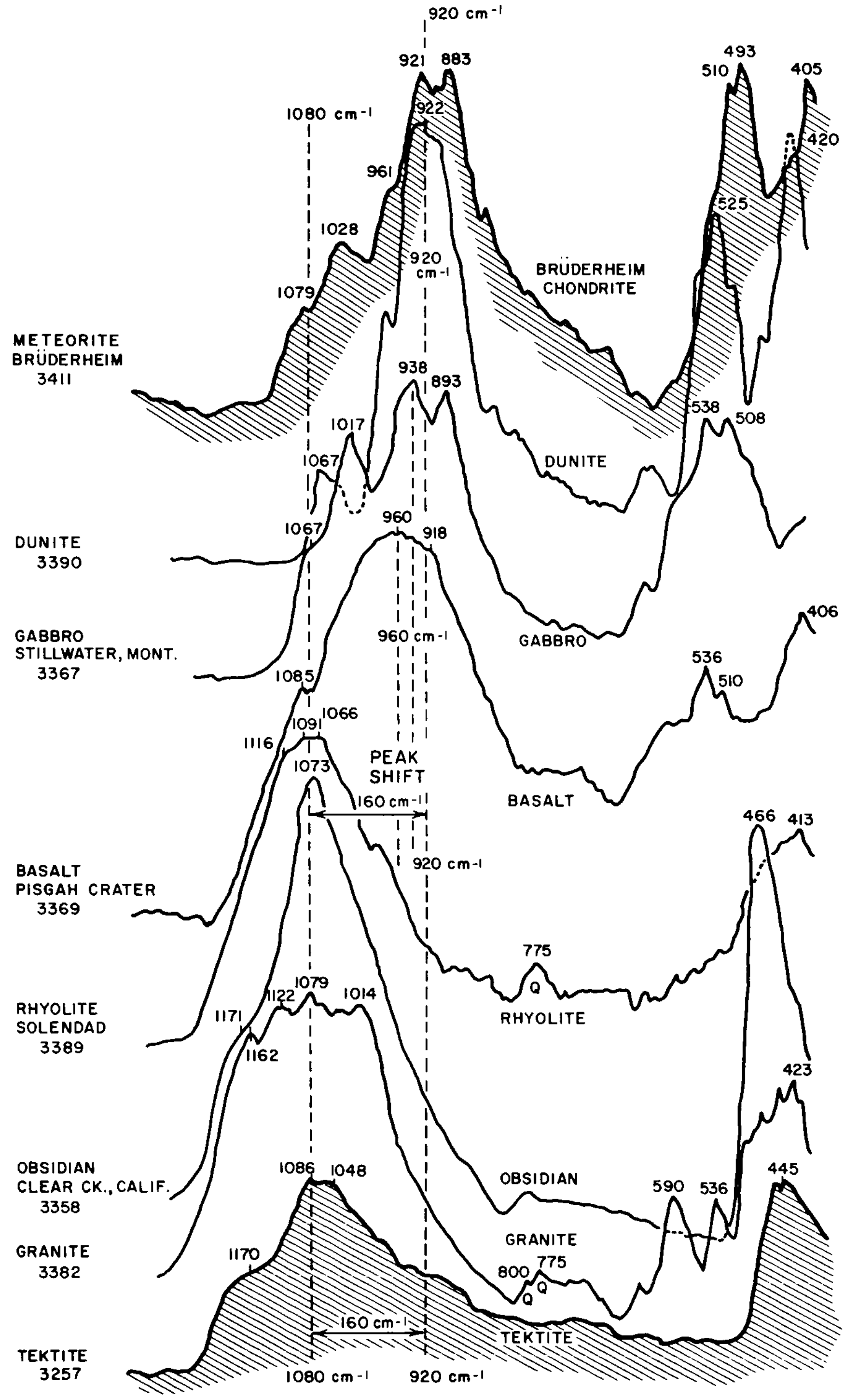


FIG. 3 INFRARED REFLECTANCE SPECTRA OF TEKTITES AND CHONDRITIC METEORITES

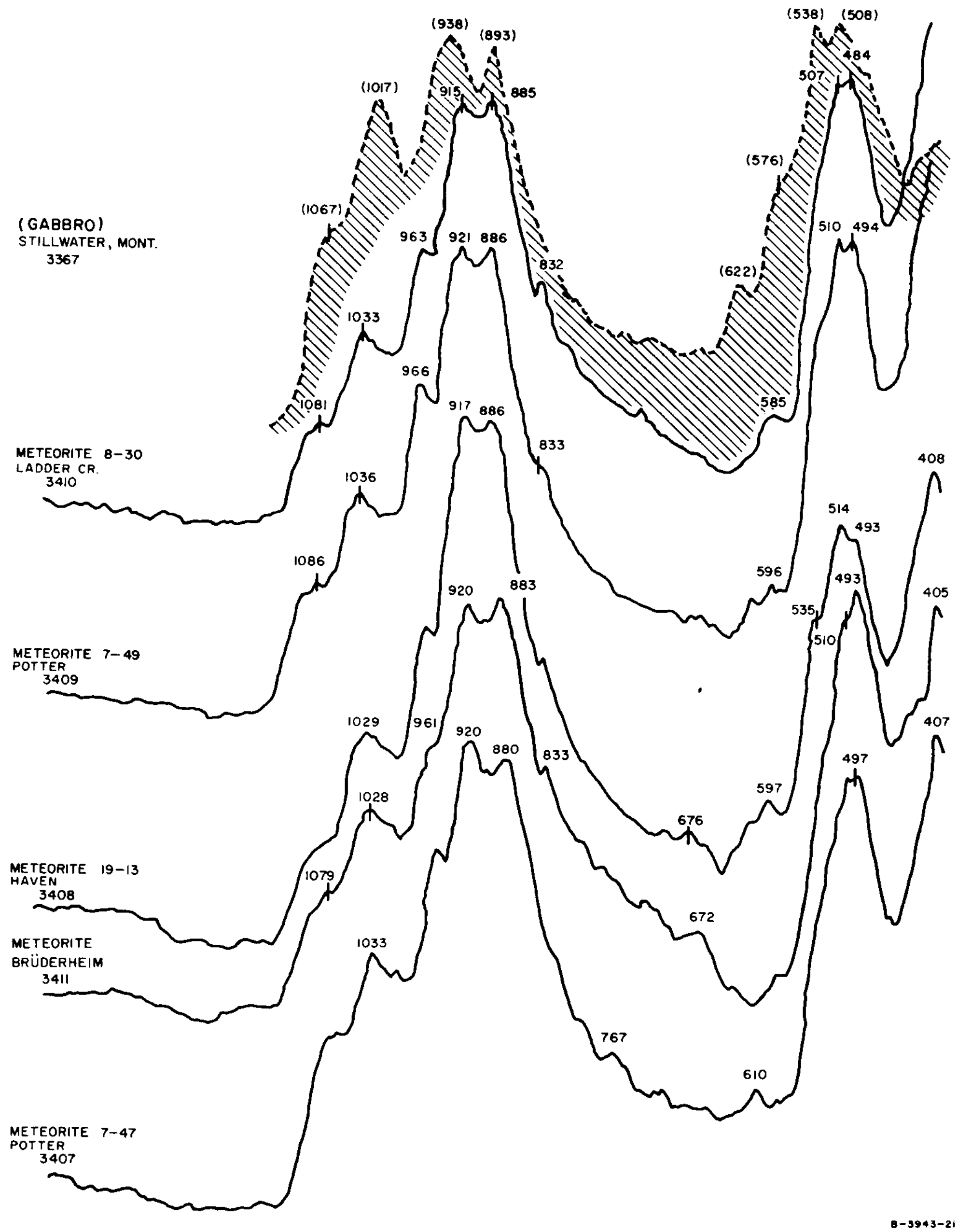


FIG. 4 INFRARED REFLECTANCE SPECTRA OF METEORITES COMPARED WITH STILLWATER GABBRO

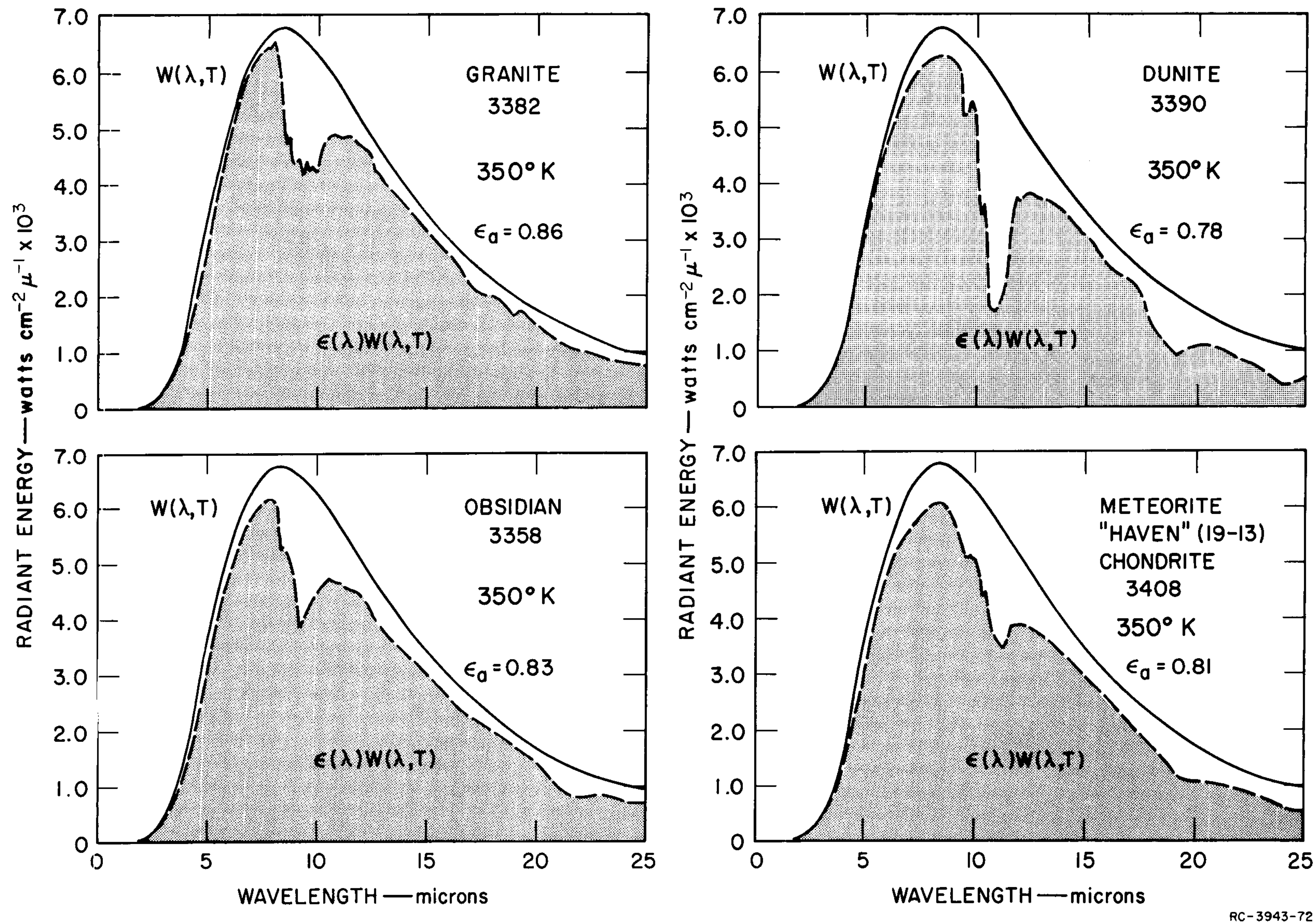


FIG. 5 350°K BLACK BODY EMISSION CURVES COMPARED WITH FOUR GRAY BODY EMISSION CURVES AT 350°K

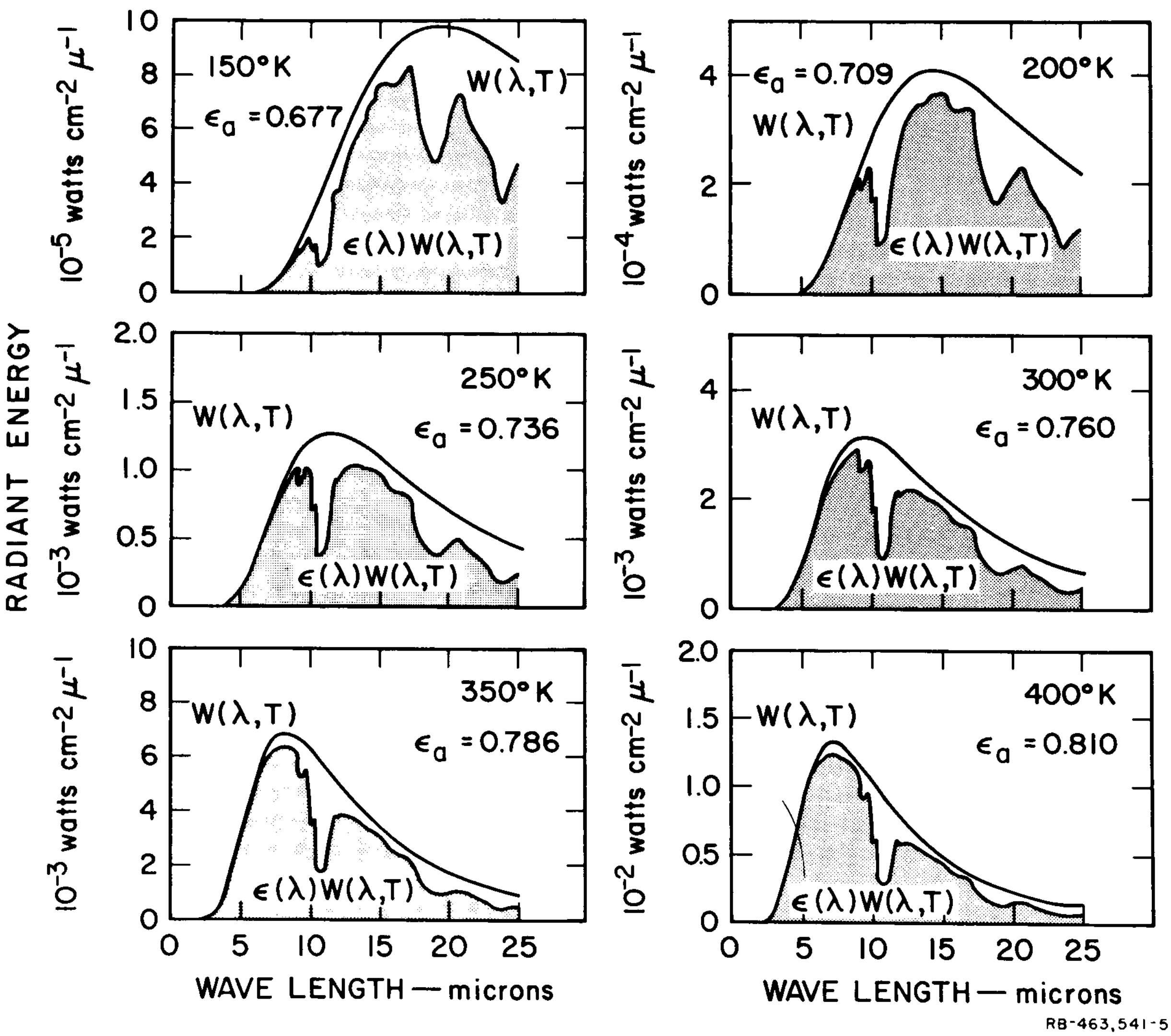


FIG. 6 EMITTANCE OF DUNITE AND A BLACK BODY AS A FUNCTION OF WAVE LENGTH AND TEMPERATURE

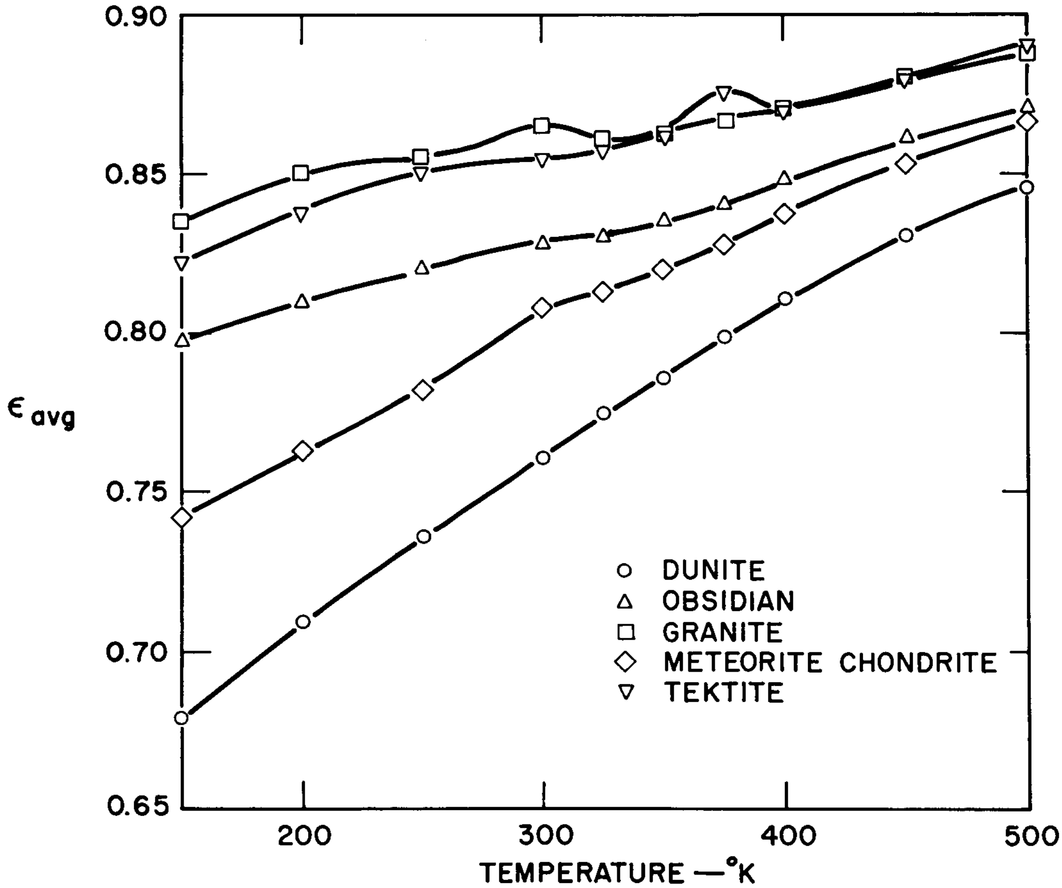


FIG. 7 CALCULATED AVERAGE EMISSIVITY AS A FUNCTION OF TEMPERATURE